Decline of Subpolar North Atlantic Circulation During the 1990s

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Observations of sea surface height reveal that substantial changes have occurred over the past decade in the mid- to high-latitude North Atlantic Ocean. TOPEX/Poseidon altimeter data show that subpolar sea surface height increased during the 1990s, and the geostrophic velocity derived from altimeter data exhibits declining subpolar gyre circulation. Combining the data from earlier satellites, we find that subpolar circulation may have been weaker in the late 1990s than in the late 1970s and 1980s. Direct current-meter observations in the boundary current of the Labrador Sea support the weakening circulation trend of the 1990s and, together with hydrographic data, show that the mid- to late 1990s decline extends deep in the water column. Analysis of the local surface forcing suggests that the 1990s buoyancy forcing has a dynamic effect consistent with altimetric and hydrographic observations: A weak thermohaline forcing allows the decay of the domed structure of subpolar isopycnals and weakening of circulation.

Extreme fluctuations in atmospheric forcing of the subpolar zone of the North Atlantic Ocean, reflected by the North Atlantic Oscillation (NAO), have occurred over the past 30 years (*1*). These changes have demonstrably affected the water column and ocean circulation, as we show here with altimetry and in situ measurements.

The subpolar gyre of the North Atlantic circulates cyclonically between 50° and 65°N and contains strong boundary currents. It is a region of intense interaction between ocean and atmosphere: Wintertime cold winds remove heat at rates of several hundred watts per square meter, resulting in deep convection reaching as far as 2500 m below the surface. Newly formed subpolar waters combine with dense Nordic Sills overflows to provide the origins of North Atlantic Deep Water (NADW).

The subpolar North Atlantic undergoes a prominent decadal-to-century variability in its hydrographic properties (*2–8*). During the 1990s, in situ data from the Labrador Sea show decreased deep convection since 1996. This period of strong hydrographic change overlaps the TOPEX/Poseidon mission, which provides an opportunity to derive large-scale variability in the subpolar North Atlantic. Recent studies using TOPEX/Poseidon data have documented large changes between the early and later 1990s (*9–11*). These changes have been interpreted as being driven by a shift in the NAO that took place in the winter of 1995–1996, moving the location of the subpolar frontal system (*11*). In addition, long-term hydrographic measurements from the eastern subpolar gyre show a decreasing trend, implying variation in southward-flowing deep water masses and extending back several decades (*12*).

Satellite observations of sea surface height (SSH) variations are usually interpreted in terms of heat storage, which at temperate latitudes and tropics is mainly determined by (adiabatic) vertical movement of isopycnals due to local and/or remotely forced dynamics. Toward high latitudes, SSH is affected by an increasing salinity contribution to seawater density and, owing to decreasing density stratification, by an increasingly barotropic (depth-independent) flow structure. In our study, the interpretation of SSH changes depends on the relative contribution of dynamics and local heat flux to heat storage in the subpolar gyre, where strong surface cooling can modify the stratification down to the deepest water masses. The dynamic impact of changes in ocean heat storage depends on their depth penetration, with deeper thermal anomalies bearing more potential energy and more baroclinic transport. For this reason, in situ current and hydrographic observations are important in validating inferences from altimetry data.

Altimetry data analysis. We use the archived 1°-resolution TOPEX/Poseidon data, which has been combined with ERS-1/2 data into the NASA Pathfinder data set. The Pathfinder data set also includes the Seasat and Geosat data, which are referenced to TOPEX. The height fields are validated against the World Ocean Circulation Experiment (WOCE) global tide gauge network and the inverse barometric effect has been removed; various atmospheric corrections have also been applied. The accuracy of the TOPEX/Poseidon altimeter is about 4 cm, whereas that of Seasat and Geosat is on the order of 10 cm or more. The altimeter cannot resolve narrow currents lying close to coasts or ice cover.

Climatological SSH in the North Atlantic is low in the cyclonic subpolar gyre and high in the anticyclonic subtropical gyre. This surface topography reflects the thermocline structure and the sense of rotation of the gyres. We used empirical orthogonal function (EOF) analysis to investigate the monthly anomalies superimposed on this climatological state. The leading EOF mode of the SSH from the TOPEX/Poseidon-ERS-1-2 data (explaining 11.1% of the variance) has a spatial pattern of opposing sign SSH anomalies located over the Gulf Stream and over the western and northern side of the subpolar gyre (Fig. 1). The time series of this pattern displays a decade-long trend. PC1 and EOF1 jointly describe an increasing SSH over the subpolar gyre but decreasing SSH over the Gulf Stream. The trend in the subpolar gyre ranges from 4 to 9 cm/decade, greatest in the Irminger Sea. This could suggest changes in the convective processes driven by orographic winds or cooling in the wake of Greenland, as has been stressed recently (*13*). The dynamic height anomaly (referenced to 1000 m) calculated from hydrographic observations (Fig. 1) (fig. S3, Bedford Institute of Oceanography AR7/W section) compares well with the actual altimeter SSH anomaly from the central Labrador Sea, as also shown in Fig. 1B.

Altimetric SSH anomalies, whatever their origin, balance geostrophic velocity anomalies, in part corresponding to changes in gyre circulation. The geostrophic velocities are computed from SSH smoothed once by Laplacian filter. Because SSH variability for the period May 1992 to April 2002 is dominated by a trend, a linear trend (from the least-squares method) in the geostrophic velocity field is recovered. Trend vectors suggest a weakening gyre circulation because the subpolar pattern resembles the mean gyre circulation inferred from hydrography and velocity observations but with opposite sign (Fig. 2). Off the Labrador Coast the velocity decline is 1 to 1.5 cm/s per decade, which, with approximate width of 500 km and depth of 1500 m, would correspond to about 7 to 10 Sv (1 Sv = 10^6 m^3/s) change in transport. Observational estimates have roughly 40 Sv total transport in the Labrador Sea boundary current; thus, the decline is a significant fraction of the mean flow. The course estimate is consistent with the interannual transport variability of the Labrador Boundary Current from 1992 to 1998 computed

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using AR7/W hydrography and SSH gradient along two altimeter tracks (*9*).

The trend vectors (Fig. 2) correspond well with the shape of the western subpolar gyre; the mean circulation involves boundary currents along the Iceland-Scotland Ridge and around the Labrador Sea. The total northward flow has components in mid-basin, along the Reykjanes Ridge toward Iceland, and also in the eastern basin, feeding the northward flow of warm Atlantic water to the Nordic seas. Observations using drifting buoys and deep neutrally buoyant floats (drifting at fixed pressure level; called RAFOS floats) all support the multiple and time-variable pathways of northward circulation in this region, with strong recirculation gyres. In particular, isopycnal RAFOS floats show circulation at about 600 m depth resembling (with opposite direction) our surface trend map, with much of the Gulf Stream water recirculating within the western subpolar gyre rather than extending far to the east (*14–18*).

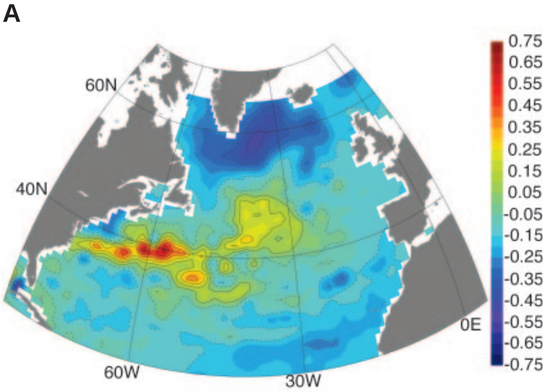
The *t* test for the significance of the trend is performed for both vector components separately, and the larger one is chosen to indicate the significance of the trend vector. The resulting distribution of *t* test values shows the trend to be more significant in the subpolar gyre than in the subtropics. This finding suggests that the subpolar ocean is particularly suitable for detecting decadal climate signals on basin scales. The same signal is likely to exist elsewhere in the North Atlantic, but the signal-to-noise ratio is poor.

Altimeter data are also available for two months in 1978 (Seasat) and for nearly 4 years during the 1980s (Geosat). In an EOF analysis we can combine all the satellite measurements to infer the gyre strength (assuming that the EOF is stable) at these separate time intervals. The first EOF pattern (EOF1) of the geostrophic velocity field contains 9.4% of the total variance when the velocity components are normalized by the standard deviation of the current speed anomalies (i.e., reducing the Gulf Stream "dominance" that is apparent in fig. S1 of early TOPEX and Geosat velocities) and then smoothed temporally by four binomial filters. (The variance of the first mode increases to 16% for the TOPEX period with nearly identical spatial pattern of vectors.) EOF1 (Fig. 3A) displays nearly the same pattern as the trend map (Fig. 2) but with opposite sign, because the EOF1 currents are chosen to align with the climatological circulation.

The corresponding time series (first principal component PC1; Fig. 3B) shows that the Seasat and Geosat periods appear to be about the same strength, but the 1990s data show a large amplitude change, with a maximum in the beginning of the 1990s (during years with a high NAO index) and the lowest strength in the late 1990s (during years with a negative or moderate NAO index). We caution that Seasat and Geosat have considerably larger errors than TOPEX/Poseidon. However, differencing the 44 months of the Geosat data and the first 44 months of the Pathfinder ERS-TOPEX data (fig. S1) yields the same large-scale pattern as in the EOF analysis. The coherence over the large basin scales supports the significance of the differences in the gyre strength indicated by the EOF analysis.

Conclusions. Altimetric geostrophic circulation observations and supporting deep-sea current-meter observations suggest significant changes over the last two decades, with increasing SSH and weakening subpolar gyre circulation in the 1990s. By comparing the dynamic consequences of three mechanisms, buoyancy forcing and barotropic and baroclinic response to local wind stress curl, we find that the gyre weakening in the 1990s is not attributable to local wind stress changes associated with NAO. The weakening-gyre scenario of the 1990s parallels the warming in the central subpolar gyre, which is the well-observed relaxation of the water column following the intense winter convection period of 1989–1994. The lack of deep convection is the oceanic response to the local buoyancy forcing, which has mimicked low-NAO heat fluxes even though the index itself has reversed itself twice during the 1990s.

Because we lack SSH data before 1978, we cannot determine whether the 1990s slowing gyre is a part of a decadal cycle or the beginning of a longer term trend. Because Labrador Sea processes are intimately linked to the meridional overturning circulation, involving both intermediate-depth and deep waters, these observations of rapid climatic changes over one decade may merit some concern for the future state of the MOC. Continuation of the altimeter missions will allow us to follow the evolution of this subpolar signal and its influence on the North Atlantic. Field observations of the subsurface oceanic circulation, hydrography, and ice cover (*28*) will be of great importance in establishing the origin of these climate shifts.



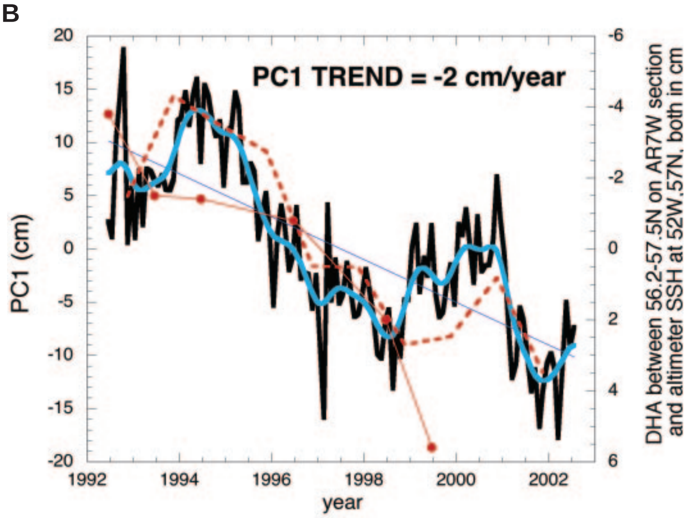


Fig. 1. (**A**) EOF1 of altimeter SSH and (**B**) its PC1 with 11.1% of the variance. EOF1 is nondimensional with contour interval of 0.05. The trend in PC1 is significantly different from zero at 95% level. The blue curve is the binomially smoothed PC1. The dynamic height anomaly (in solid red; dots denote data points of the time series) computed in the central Labrador Sea (average from 56.2° to 57.5°N along the WOCE AR7/W section across the Labrador Sea from Newfoundland to Greenland) is shown in (B) with its axis on right. The altimeter SSH anomaly at 52°W, 57°N (12-month May-to-April average; dashed red) in the central Labrador gives a similar result of about 8 cm from 1994 to 2002.